UNCLASSIFIED

AD NUMBER
ADA071931
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; 06 JUN 1978. Other requests shall be referred to Naval Submarine Medical Research Laboratory, Box 900 Naval Submarine Basse, Groton, CT 06340.**
AUTHORITY
NMRDC per DTIC form 55

THIS PAGE IS UNCLASSIFIED

821

The ability of color defectives to judge signal lights at sea

Jo Ann S. Kinney, Helen M. Paulson, and Arthur N. Beare
Naval Submarine Medical Research Laboratory, Groton, Connecticut 06340
(Received 6 June 1978)

Measures were made of the ability of color-defective men to judge correctly the colors of navigation lights (red, green, or white) presented to them at night under realistic sea conditions. Eighty-one color-defective men were employed; they were categorized as to type and degree of defect using a battery of five color-vision tests. While the average performance of the color-defective men was considerably poorer than that of 24 color normals, there were large individual differences within each category of defect. Attempts to account for these differences in performance by variations in acuity, intelligence, and motivation failed. The extent to which the data can be accounted for by modern color-vision theory is discussed.

INTRODUCTION

Color coding is widely employed to facilitate the rapid transfer of information; consequently color-vision requirements exist for many occupations. Examples include railroad engineers, airplane pilots, and Naval line officers. Establishing the requirements for specific jobs can be done either theoretically[1] or empirically.[2]

Theoretical predictions are complicated, however, by the wide range of variations in degree of defect evidenced among the common color defectives. The largest group of color defectives are the anomalous trichromats, a category which accounts for nearly 70% of the defects among males in the U.S. These individuals have been the subject of many investigations all of which agree on the large individual differences found among anomalous trichromats. For example, variations among deuteranomalous extend from those with almost normal vision to those who are difficult to differentiate from

deuteranopes; this is found for luminosity functions, wavelength discrimination, saturation discrimination,[3] and for color naming.[4] Obviously some color tasks can be easily performed by some anomalous trichromats and will be very difficult to impossible for others.

These extreme individual differences have long been recognized and a number of attempts made to categorize the anomalous as to degree of defect. The most common test is the anomaloscope which differentiates protans from deutans and can be employed to distinguish simple and extreme anomalous from dichromatic. The Hardy-Rand-Rittler plates grade examinees as mild, moderate, or severe. However, no single test has proved completely effective; comparisons among the various categories yield a variety of misclassifications.[5] The modern consensus is that a battery of tests is required to adequately differentiate among the various types and degrees of defect.

On the empirical level, a number of investigators have studied the ability of color defectives to perform color related tasks required by various occupations. These tasks include classification and sorting of color-coded electronic components;[6,7] identification and reaction time to traffic lights;[8,9] identification of colors in aviation lighting;[10–12] and urine analysis by color matching tests.[13] Some of the investigators have classified their color-defective subjects while others have simply differentiated normals from defectives.

Three generalizations can be made from the studies: (i) on the average, color defectives' performance is always poorer than color normals; (ii) protans tend to be worse than deutans;[2,7,9] and (iii) attempts to correlate the results on a specific color task with scores on color-vision tests or with classifications of the men according to degree of defect are frequently disappointing. Thus, for example, Nathan *et al.* report that "Neither the anomaloscope range nor quotient gives any indication of the ability of color defectives to recognize colors of traffic lights."[9] Similarly, Steen *et al.* graded subjects according to degree of defect on the anomaloscope. While on the average, those with lesser defects performed better judging the colors of the light gun than did those with greater defects, there were some men in every category, from mild to dichromatic, both protan and deutan, who scored perfectly on the practical test.[10] Again, Sloan and Habel[12] studying color naming of red and green point sources by color defectives as a function of illumination level, found within each category of defect (as defined by H-R-R plates), some men who always passed and some who always failed the color naming task.

This report is of another attempt to predict the performance of color-defective men on a practical task—that of judging the colors of navigation lights at sea. Current standards for commissioning Naval line officers require normal or near-normal color vision. Since approximately 7% of American males cannot meet this standard, a significant number are being excluded. This study was undertaken to determine whether more color defectives might be acceptable. It differs from previous attempts in that the men were tested on a battery of color-vision tests and carefully categorized as to mild, moderate, severe, or dichromatic protans or deutans. It was expected that, with careful screening, additional categories of men could be identified who were capable of performing the task.

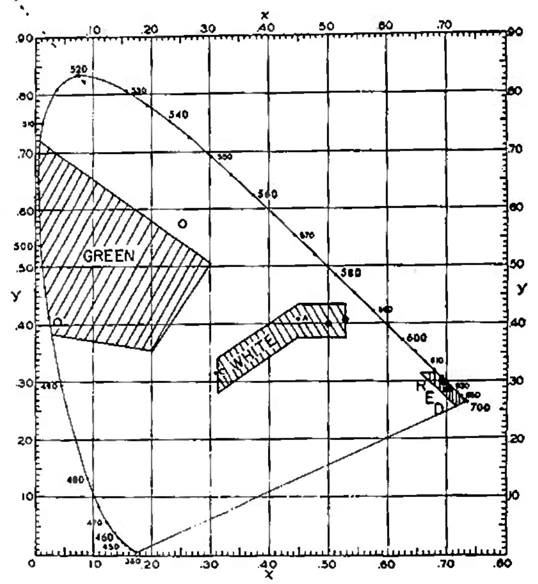

FIG. 1. CIE chromaticity diagram showing the extreme range of the green (O), white (●), and red (▲) running lights from this study and, in the hatched areas, the new international standards.

Experimental procedure

The experiment was conducted at night at the U.S. Naval Academy using midshipmen as subjects. They stood on the sea wall at the Academy, looking toward the open Chesapeake Bay, and judged the colors of lights presented from three yard patrol boats anchored at one, two, and three miles from the sea wall.

Each boat was outfitted with three ship's running lights, a red, a green, and a white, taken from destroyers at the Philadelphia Shipyard. The three lights were mounted side-by-side on a rack at the top of the boat's bridge and were equipped with switches so they could be individually turned on and off.

Chromaticities of the lights are presented in Fig. 1. The differences among lights of the same color are small for the red and white lights but are sizable for the green.[14] Both blue-green and yellow-green running lights are common throughout the navies and merchant ships of the world and this range of differences is representative. New, internationally agreed standards,[15] also shown, will eliminate some but not all of the yellower-greens currently in use.

The intensity of the lights and their illuminance in the plane of the eye are given in Table I. On each boat, the white light was the brightest, with the red and green lights more comparable. The 3 in. globes at 1, 2, and 3 miles subtended angles at the eye of 10, 5, and 3 seconds of arc, making them all essentially point sources.

The distances and positions of the boats were selected so that the scene, to the observer, would be of representative, tiny, colored lights of variable brightness at indeterminate distance, viewed against a dark surround. The boats were positioned so that their lights were viewed along approximately the same line of sight but without interference with one another. The positions were also chosen so that there were no shore lights in the immediate background and the boats themselves were not visible from shore.

TABLE I. Intensities of signal lights.

Color	Boat A at one mile Candle-power	Sea-mile candles*	Boat B at two miles Candle-power	Sea-mile candles*	Boat C at three miles Candle-power	Sea-mile candles*
White	66.6	53.2	19.1	3.1	30.6	1.7
Green	6.8	5.4	5.3	1.0	5.4	0.3
Red	7.6	6.1	5.4	1.1	7.2	0.4

* Illuminance is calculated in sea-mile candles, the common unit for signal lights, assuming an atmospheric attenuation of 0.8/mile.

Lights are presented one at a time for 10 s. There were 120 presentations or trials during each evening's run. Each light (red, green, or white) was shown from each boat 10 times. In addition, 30 "no light" trials were included so that color defective individuals, who might know they cannot see specific colors, could not obtain the correct answer by inference. The predetermined order of presentation was randomized among the colors and the boats; this order was maintained by radio communication between the shore and the boats. Trial numbers were announced over a loud speaker. The midshipmen were equipped with clipboards and data sheets on which they checked which light (red, green, white, or none) they had seen on each trial. Prior to the experiment, the men were given instructions, shown the positions of the boats (by signals from the masthead lights), and given 15 practice trials followed by a period of questions and answers.

The experiment was conducted on two successive nights, with approximately 50 midshipmen making judgments each night. The entire experiment was rehearsed the previous night. The distances were selected empirically during this rehearsal to range from an easy to a somewhat difficult task for individuals with normal color vision. The weather on all three nights was clear and cold with no moon. Visibility was excellent with lights on the far shore of the Bay (7 miles away) clearly visible each night.

The subjects

A number of color-defective midshipmen were available in the classes of '77 through '80. Many of these men were mild color defectives (as determined by the Farnsworth Lantern Test) and were qualified to become unrestricted line officers since the Naval screening standard was purposely designed to pass men who have a mild defect. Others with more severe color-vision defects had entered Annapolis with the understanding that they would be eligible only for commissioning in the Marine Corps or the Navy Staff Corps.

The experiment required that the men be categorized according to their color-vision defect; this was accomplished by the use of the test battery developed at Naval Submarine Medical Research Laboratory.[16] The battery consists of a group of tests (Pseudoisochromatic plates, Farnsworth Lantern, D-15, H-16) that are graded as to difficulty so that the individuals with the most severe color-vision defect fail all the tests while those with milder impairments fail progressively fewer tests. Classification as to protan or deutan was verified with the Hecht-Shlaer anomaloscope.

TABLE II. The type and degree of color-vision defect among the midshipmen participating in the experiment ($N = 81$).

Degree	Protan	Deutan
Mild	13	17
Moderate	6	18
Severe	7	5
Dichromatic	2	13
Total Number	28	53

The number of men in each category of color defect is shown in Table II. Approximately equal numbers of men in each category were assigned to each night's testing. In addition, 24 midshipmen with normal color vision were included in the experiment to provide a baseline for comparison.

RESULTS

The results for all distances and lights combined are presented in Table III in terms of the average percentage of correct responses. The color-defective men, on the average, did considerably poorer than color normals and evidenced more variability. While, on the average, the mildly-defective individuals achieved better scores than the other color-defective men, there was no systematic degradation of performance with increasing degree of defect. An analysis of variance was performed on these data which showed significant differences ($p < 0.01$) for colors, distances, and interactions of color by distance, color by group (diagnostic category), and color by distance by group. Group differences were highly significant if color normals were included but just approached the 0.05 level if normals' data were excluded.

The percentage of correct responses[17] for each color at each distance are presented in Figs. 2 through 4. Data for the color normal men are presented for comparison. The data for the severe and dichromatic men have been combined because of the small number of men in these categories. At the one mile distance (Fig. 2), the color normals were correct more than 99% of the time. If the running light was red, the color defective men did well too (the lowest percentage correct responses

TABLE III. The average percentage of colored lights judged correctly by each color-vision group.

Groups			Mean
Color Normals			94.8 ± 5.1
Color Defectives:	Protans	Deutans	
Mild	71.5 ± 17.8	83.6 ± 9.6	78.3 ± 14.5
Moderate	72.2 ± 5.2	68.8 ± 13.2	69.6 ± 11.4
Severe & Dichromatic	62.2 ± 9.5	76.9 ± 13.8	72.0 ± 13.9
Mean	68.6 ± 13.9	76.3 ± 13.6	73.7 ± 14.0

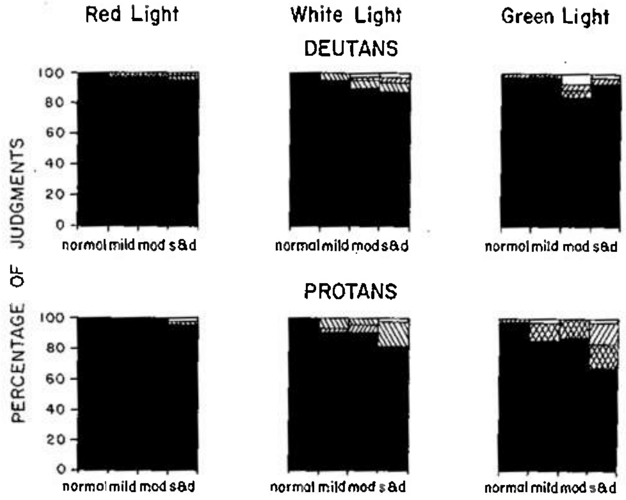

FIG. 2 Percentage of red, white, and green signal lights judged correctly and incorrectly at a distance of one mile. The responses of the deutans are at the top and the protans, the bottom. Color normals' judgments are included in each for comparison. Solid areas are correct responses; clear areas refer to no response; and the hatched areas, incorrect color responses (/////) red; (\\\\\) green; (XXXXX) white.

being 95% for the severe and dichromatic deutans). More errors were made by the color defective men when the light was white or green. The protans experienced more difficulty with these lights than did the deutans.

At two miles (Fig. 3), the differences between the men with normal and defective color vision became more pronounced. At this distance, color normals are still performing at 95% correct responses or better, while the color defective men dropped to 50% correct, in the worst cases.

At three miles (Fig. 4), the color normals see 88% of the lights correctly but the color defectives' performance has deteriorated still further. While most of the errors made by normals are failures to see the lights, the deutans both fail to see lights and confuse those they do see. For example, when the moderate deutans judged red they were wrong 56% of the time; they failed to see it 17% of the time and called it green

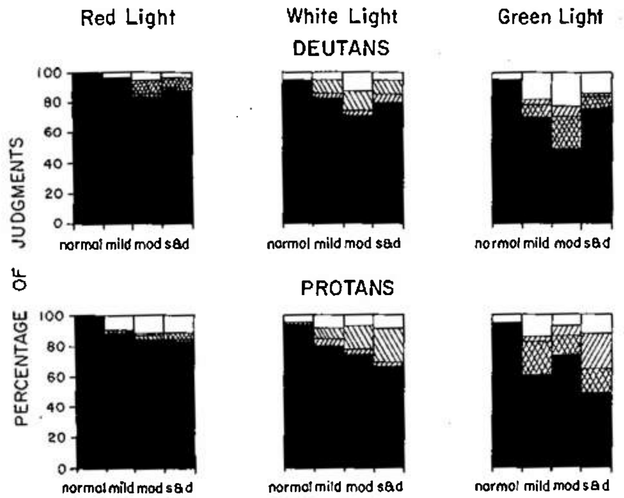

FIG. 3. Percentage of red, white, and green signal lights judged correctly and incorrectly at a distance of two miles. The coding is the same as Fig. 2.

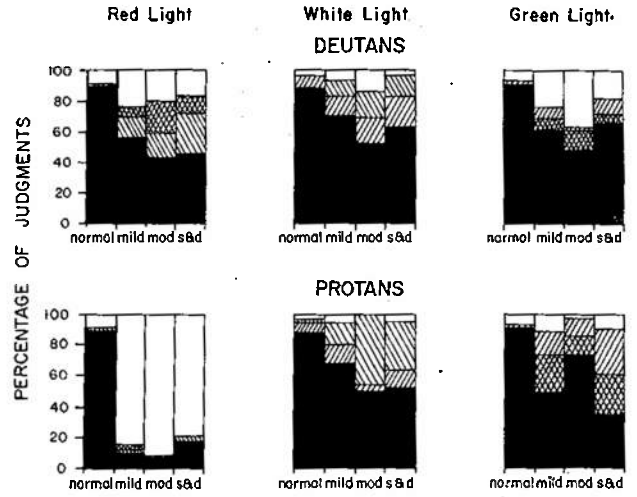

FIG. 4. Percentage of red, white, and green signal lights judged correctly and incorrectly at a distance of three miles. The coding is the same as Fig. 2.

or white 39% of the time. When the running light was white, they called it red or green 33% of the time. Less than 20% of the red lights were reported correctly by any of the groups of protans; in fact, 61% of the men with a protan defect *never* saw even one of the most distant red lights.

The conclusion from this analysis is that men with normal color vision performed the task well, while color-defective individuals did relatively poorly. However, there were very large individual differences in performance among the color-defective men.

Individual differences in performance

Individual differences in performance are shown in Table IV, which gives the range, from best to worse, in each category and in Fig. 5 which shows the total distribution of scores for color normals, deutans, and protans. A significant number of the color-defective men do as well as the poorer color normals. In fact, 11 of the color defectives did as well or better than the worst-three color normals and 26 color defectives did better than the worst color normal. These 26 men came from all three grades of deutans and from the mild protan group.

There are a number of factors which might explain these individual differences in performance. Some are related to color vision and others are not. Among the latter are varia-

TABLE IV. The range of correct responses of red, green, and white lights in each subject group.

Group		Best Percent	Worst correct	Percent as good as worst normal
Color Normals		100	81	
Color Defectives:				
Protans:	Mild	96	31	31
	Moderate	79	65	0
	Severe & Dichromatic	74	46	0
Deutans:	Mild	95	49	67
	Moderate	93	54	18
	Severe & Dichromatic	95	46	39

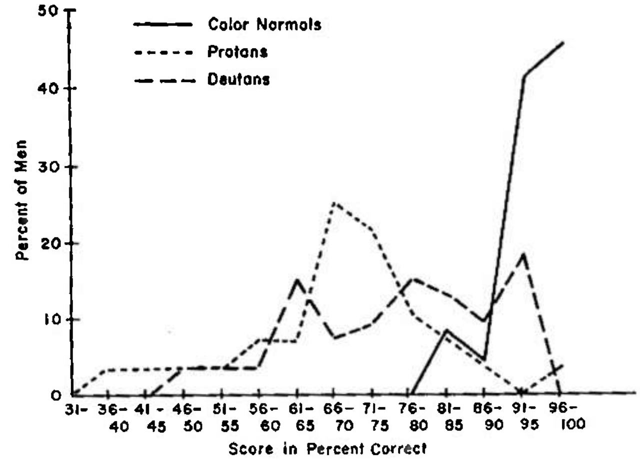

FIG. 5. Distribution of scores, in total percent correct, of color normals, protans, and deutans.

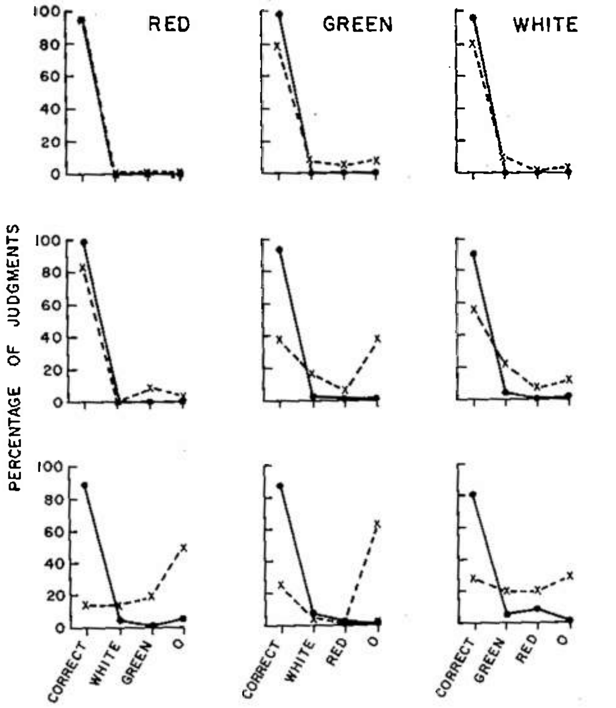

FIG. 6. Comparison of the judgments made by the best (O—O) and poorest (X- - -X) 22% of the deutans, from top to bottom, at one, two, and three miles.

tions in visual acuity, experience judging lights at sea, intelligence, and motivation. Information on these variables was obtained from the men's personnel and health records. These data were analyzed with respect to the performance on the colored lights for the group as a whole and in addition, for the top and bottom 15% of the color-defective men, selected on the basis of their performance judging the running lights.

Corrected acuity of less than 20/20 was found for only one midshipman in the bottom 15% of the color defectives. Visual acuity, therefore, cannot account for the performance differences. Sailing experience, which may have provided the midshipmen with additional cues to help them judge signal lights at sea, also failed to differentiate between groups. Of the six men whose records showed sailing as a primary sport, none was in the best group of color defectives.

Correlations between performance and Cumulative Periodic Quarterly Ratings (CPQR), Scholastic Aptitude Test, Verbal (SATV) and Scholastic Aptitude Test, Mathematical (SATM) scores for all subjects were close to zero. Comparisons between the top and bottom 15% of the color defectives showed small differences in grades and SAT scores, but none of these differences was significant. Motivation (at least for academic achievement) was determined by comparing an individual's grade (CPQR) with his ability (as indicated by the SATV and SATM scores). No differences were found between the top and bottom 15% on this measure.

It is concluded that the individual differences in performance within categories of color-vision defect have not been accounted for by available indices of intelligence, motivation, or experience and probably are the result of subtle differences in color vision which are not assessable by our battery.

An attempt to identify these factors was made by comparing the errors of the poorest subjects with those of the best at each of the three distances. For the deutans, the poorest group consisted of 12 men (22% of the deutans) whose overall percent correct identifications was less than 64%; this group consisted of 1 mild, 8 moderate, 1 severe, and 2 dichromatic deutans. The best group, 12 men whose overall performance was 90% or better, consisted of 6 mild, 2 moderate, 1 severe, and 3 dichromatic deutans.

The judgments of these two groups of deutans are compared in Fig. 6. The best men make very few errors under any conditions; their performance is indistinguishable from that of the normals. The performance of the poorest men differs in two important respects. First there is a marked deterioration with distance: while their performance at one mile is quite good, at three miles the men are not even performing at chance level. Even at two miles, their identification of green and white is severely impaired. Second, by far the most common error made by these men is calling a signal "no light." This failure to see the signal was greatest for the green light but also occurred for red and white at three miles. In fact, 63% of the total errors made at this distance were missed signals.

A similar comparison of the errors made by the best and poorest protans was made; since there are fewer protans, 21% of the group is only six individuals. Also, since the protans did not perform as well overall as did the deutans, performance as poor as 76% correct must be counted among the "best" six; these six were all classified as mild protans. The worst men had scores of less than 60% correct; this group includes 2 milds, 3 severes, and 1 dichromatic protan.

The comparison of judgments by these two groups of protans is shown in Fig. 7 and differs considerably from that of the deutan group. First, differences between the groups are apparent only for the green and white signals; for the red, performance of the best and the poorest protans is almost indistinguishable. Second, for the worst protans, identification of the green and white signals is poor even at the easiest conditions of one and two miles. The most common errors for these men are identifying a green signal as white and vice versa; at three miles, green and white are also frequently called red.

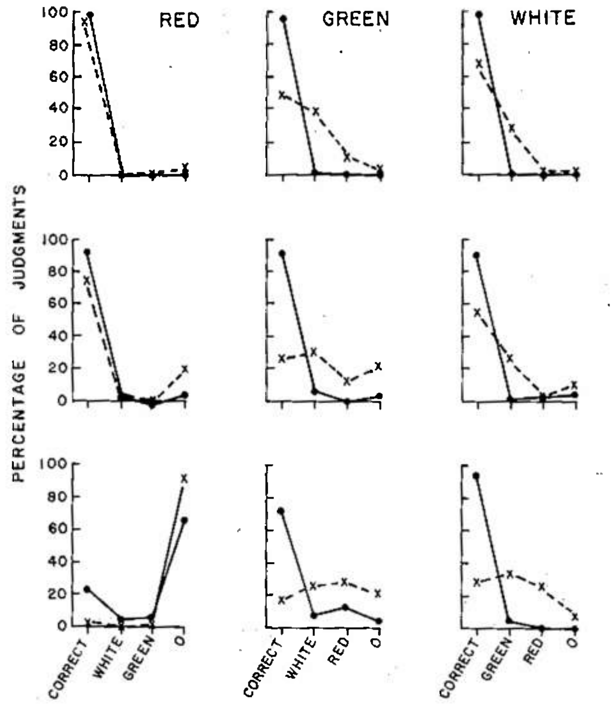

FIG. 7. Comparison of the judgments made the best (O—O) and poorest (X- - -X) 20% of the protans, from top to bottom, at one, two, and three miles.

DISCUSSION

The performance of color-defective individuals, judging the color of running lights at sea, was poorer overall than that of color normals and characterized by large individual differences within each category of defect; the latter was particularly true of the performance of deutans. Once again the major finding of interest is the inability to predict with certainty, despite the careful pre-screening, which men will do well in the practical situation and which will not. The tests in the battery measure widely different aspects of color vision and some of these may not be related to judging lights at sea; the possibility thus arises that the Farnsworth Lantern alone might be more useful for predicting performance at sea than the battery. That this is indeed the case is shown in Table V which gives the correlations between results on individual tests of the battery and performance at sea. Since most of the tests are of the pass–fail variety, the correlations are point-biserial. On the Farnsworth Lantern, however, errors were also tabulated, so two correlations are possible, one for the pass–fail criterion and the other with number of errors. Both yield small but significant ($p < 0.05$) correlations in the right direction.[18] Nonetheless, the correlation is too small to be useful for selection. A redesign of the Farnsworth Lantern to improve the correlation with this task is possible and under investigation.

Major advances to the understanding of color vision have been made in recent years and the extent to which these data can be explained by modern color theory is worth considering. Most recognized theories today are stage theories in which the neural outputs of three cone photopigments are combined in various ways. While details of the combinations vary, all theories provide an additive luminance system, and an opponent or subtractive hue system both of which contribute to

TABLE V. Correlations between performance at sea and individual tests from the battery.

Test	r
Farnsworth Lantern	
Pass/Fail	0.33
Error	−0.30
D-15	0.11
H-16	0.05

perception.[19] Protanopes lack the long wavelength and deuteranopes most likely lack the medium wavelength photopigment[20] while anomalous trichromats have one or more abnormal photopigments whose absorption spectra are shifted toward longer or shorter wavelengths.[21]

When viewed in the context of this theory, the performance of protans is relatively straightforward. Their overall scores were again poorer than that of the deutans.[2,7,9] A major portion of their errors results from an inability to see distant (weak) red signals and this is equally true for both the best and the poorest men. This general luminosity loss for both protanopes and protanomalous has been widely recognized for years,[3] and is attributed to lack of a normal long wavelength photopigment. Their next most common error is confusion between green and white, a result readily predictable from protan confusion loci for these lights.[3] Furthermore individual differences within protan categories were not so large as for deutans; only one mild protan achieved a total score of better than 90%; protanopes did worse than protanomalous; and the best 20% of the protan group were all classed as mildly defective. It should be noted however that the mild protanomalous did not, on the average, perform better than the moderate group.

The performance of the deutans is harder to understand, particularly the wide range of individual differences. Some deutans in each category, even dichromatic, performed nearly perfectly while others achieved 50% or less correct. Moreover, while some deutans did almost as well judging signals at three miles as at one mile, others could not do the task at all at three miles. The most common error of the latter group was failure to see the signals. In fact, the worst subjects at the closest distance performed quite comparably to the best subjects at the farthest distance. It appears that there is another factor operating to produce these extremes in performance that is not being adequately assessed by the battery.[22]

Shifts in the cone fundamental sensation curves[21] of the color anomalous, whether due to macular pigmentation or to a fundamental difference in photochemicals, cannot account for all this variability. Presumably such shifts would form the basis for the original color-vision test results: for example, individuals with small differences between the spectra of the long- and mid-wavelength cones would have great trouble differentiating hue and thus be categorized as severely defective, while those with larger differences between spectra would be mild or moderate.

The variability in performance appears to relate instead to luminosity losses. Threshold determinations of the luminosity of deutans have shown general agreement among investigators that there is a loss of sensitivity averaging about 0.3 log unit at 500 nm, when compared on an absolute energy

basis, to normals,[3,23,24] but that the range of values among deutans overlaps that of normals.

While this loss in sensitivity also is not great enough, by itself, to account for the differences in performance among deutans, additional possibilities for sensitivity losses come from the stage models of color vision, particularly from the part played by the opponent-color system. Since the contribution of the red-green system results from subtracting the mid- and long-wavelength cone outputs from one another, the more alike the two absorption spectra, the closer to zero will be contribution of this system. There is now considerable evidence that different techniques of measurement will yield different luminosity functions, depending upon whether the method taps the output of the additive-luminance system, the subtractive-opponent system, or both.[19,25]

The feasibility of this approach to understanding the individual differences among deutans rests upon the relative contribution of the opponent and luminance systems to detection under the conditions of this study, namely suprathreshold point sources of long duration viewed against a dark surround. King-Smith and Carden[26] have recently published threshold data on color normals using different experimental techniques to analyze the contributions of the opponent and luminosity systems to detection. While their data indicate that some conditions in this study, namely the small size and dark surround, would minimize the opponent contribution, Zrenner,[27] employing the visual evoked cortical potential to allow suprathreshold measurement, finds contribution of the opponent system under all conditions of size and duration. The specific conditions of this study have not been duplicated but the available evidence suggests that further analysis of the relative contributions of the luminance and opponent color systems for both normal and color-defective individuals may well explain the sizeable individual differences found in this study.

Understanding the reasons for these individual differences furthermore is essential to answering the practical question of which color-defective men might safely be employed judging signal lights at sea. Some severely color-defective men did perform well in this task, but it would be dangerous to assume that they would be equally successful under all viewing conditions. Since testing a man in each practical situation he will encounter at sea, with different colors, distances, and atmospheric attenuations, is not feasible, further research is necessary before contemplating changes in color vision standards.

ACKNOWLEDGMENT

This work is from Naval Medical Research and Development Command Research Work Unit No. M0100-PN.001-1005.

[1]D. B. Judd, *Standard Color Filters for Electronic Equipment,* (Armed Forces-National Research Council Vision Committee Secretariat, University of Michigan, 1952).

[2]L. L. Sloan and A. Habel, "Color signal systems for the red-green color blind. An experimental test of the three-color signal system proposed by Judd," J. Opt. Soc. Am. **45**, 592–598 (1955).

[3]Y. Hsia and C. H. Graham, "Color blindness," in *Vision and Visual Perception,* edited by C. H. Graham (Wiley, New York, 1965).

[4]V. C. Smith, J. Pokorny, and R. Swartley, "Continuous hue estimation of brief flashes by deuteranomalous observers," Am. J. Psychol. **86**, 115–131 (1973).

[5]Excellent reviews of the testing literature are found in B. L. Collins and J. A. Whittenburg, "Defective color vision, filters, film and the detection of camouflaged targets: an annotated bibliography," Human Engineering Laboratory, Aberdeen Proving Ground, Maryland, Mar., 1974; R. Lakowski, "A critical evaluation of color vision tests," Br. J. Physiol. Opt. **23**, 186–209 (1966); "Theory and practice of colour vision testing: a review, Part 1," Br. J. Ind. Med. **26**, 173–189 (1969); "Theory and practice of colour vision testing. Part 2," Br. J. Ind. Med. **26**, 265–288 (1969); H. M. Paulson, "Comparison of color vision tests used by the Armed Forces," in *Color Vision* (National Academy of Sciences, Washington, D.C., 1973).

[6]P. L. Walraven and H. L. Leebeek, "Recognition of color codes by normals and color defectives at several illumination levels. An evaluation study of the H-R-R plates," Am. J. Optom. & Arch. Am. Acad. Optom. **37**, 82–92 (1960).

[7]J. Voke, "Industrial Consequences of Defective Colour Vision," Ph.D. Thesis, The City University, Department of Optometry and Visual Science, London, England (1976) (unpublished).

[8]B. L. Cole and B. Brown, "Optimum intensity of red road-traffic signal lights for normal and protanopic observers," J. Opt. Soc. Am. **56**, 516–522 (1966).

[9]J. Nathan, G. H. Henry, and B. L. Cole, "Recognition of colored road traffic light signals by normal and color-vision-defective observers," J. Opt. Soc. Am. **54**, 1041–1045 (1964).

[10]J. A. Steen, W. E. Collins, and M. F. Lewis, "Utility of several clinical tests of color-defective vision in predicting daytime and night-time performance with the Aviation Signal Light Gun," Aerosp. Med. **45**, 467–472 (1974).

[11]K. N. Jones, J. A. Steen, and W. E. Collins, "Predictive validities of several clinical color vision tests for aviation signal light gun performance," Aviat. Space Environ Med. **46**, 660–667 (1975).

[12]L. L. Sloan and A. Habel, "Recognition of red and green point sources by color-defective observers," J. Opt. Soc. Am. **45**, 599–601 (1955).

[13]M. C. Fetter, "Colorimetric tests read by color-blind people," Am. J. Med. Tech. **29**, 349–355 (1963).

[14]With the ships in position, the green color differences could not be discriminated by color normals on the sea wall, since all point-source greens appear blue-green due to foveal tritanopia. The differences could, of course, aid or confuse color defectives.

[15]International Regulations for Preventing Collisions at Sea, 1972, as attached to the Final Act of the International Conference on Revision of the International Regulations for Preventing Collisions at Sea 1972. [Adopted by the Inter-Government Maritime Consultation Organization (IMCO).]

[16]H. M. Paulson, "Comparison of color vision tests used by the Armed Forces," in *Color Vision* (National Academy of Sciences, Washington, D.C., 1973).

[17]False alarms, or incorrect judgments of the 30 "no signal" condition were rare; the median number was zero for the normals, all deutans and mild protans and 1 for the moderate and severe protans. Consequently the entire analysis in this paper is based only on the judgments made when a light was present.

[18]Steen *et al.* (Ref. 10) report much higher correlations between tests of color vision and the performance on the light-gun test; however, they included data on color normals in their data base, a procedure which greatly increases the size of the correlation.

[19]Representative theories are found in L. M. Hurvich and D. Jameson, "An opponent-process theory of color vision," J. Psychol. Rev. **64**(6), 384–404 (1957); R. L. De Valois, I. Abramov, and G. H. Jacobs, "Analysis of response patterns of LGN cells," J. Opt. Soc. Am. **56**, 966–977 (1966); J. J. Vos and P. L. Walraven, "On the derivation of the foveal receptor primaries," Vision Res. **11**, 799–818 (1970); H. G. Sperling and R. S. Harwerth, "Red-green cone interactions in the increment-threshold spectral sensitivity of primates," Science **172**, 180–184 (1971); S. L. Guth and H. R. Lodge, "Heterochromatic additivity, foveal spectral sensitivity, and a new color model," J. Opt. Soc. Am. **63**, 450–462 (1973); C. Ingling, Jr., "The spectral sensitivity of the opponent-color channels," Vision Res. **17**, 1083–1089 (1977). An excellent review is available in R. L. De Valois and K. K. De Valois, "Neural coding of color," in *Handbook of Perception, Vol. V Seeing,* edited by E. C. Carterette and M. P. Friedman (Academic, New York, 1975), 117–166.

attributing deuteranopia to a missing photopigment has been much more controversial over the years than the same explanation for protanopia. For excellent modern discussions of the color theory applied to the color defective, see M. J. Alpern, J. Mindel, and S. Torii, "Are there two types of deuteranopes?" J. Physiol. Lond., 199, 443–456 (1968); L. M. Hurvich, "Color vision deficiencies," in *Handbook of Sensory Physiology Vol. VII/4 Visual Psychophysics,* edited by D. Jameson and L. M. Hurvich (Springer-Verlag, Berlin, 1972), 582–624; and M. Alpern and T. Wake, "Cone pigments in human deutan colour vision defects," J. Physiol. Lond., **266**, 595–612 (1977).

[21]An excellent review of this proposition is available in J. Pokorny and V. C. Smith, "Evaluation of single-pigment shift model of anomalous trichromacy," J. Opt. Soc. Am. **67**, 1196–1209 (1977); a new theoretical possibility in M. Alpern and E. N. Pugh, Jr., "Variation in the action spectrum of erythrolabe among deuteranopes," J. Physiol. Lond., **266**, 613–646, (1977); and M. Alpern and J. Moeller, "The red and green cone visual pigments of deuteranomalous trichromacy," J. Physiol. Lond., **266**, 647–675 (1977).

[22]One plausible explanation is that the differences are a factor of retinal subtense, since the screening tests utilize relatively large colored areas while the lights at sea are essentially point sources. Sloan and Habel[12] noted this difference also and suggested that the poorer subjects in their study had a significantly greater impairment in the fovea than in the periphery. However, this suggestion was tested in an auxiliary study, to be reported separately, and was not confirmed.

[23]G. Verriest and A. Uvijls, "Central and peripheral increment thresholds for white and spectral lights on a white background in different kinds of congenitally defective colour vision," Atti della Fondazione Giorgio Ronchi **XXII (2)**, 213–254 (1977).

[24]G. Verriest, "Les courbes spectrales photopiques d'efficacité lumineuse relative dans les déficiences congénitales de la vision des couleurs," Vision Res. **11**, 1407–1434 (1971).

[25]J. A. S. Kinney, "Is photometry still relevant to illuminating engineering?", in *Compte Rendu 18e, London, 1975* (Bureau Central de la CIE, Paris, 1976), 70–76.

[26]P. E. King-Smith and D. Carden, "Luminance and opponent-color contributions to visual detection and adaptation and to temporal and spatial integration," J. Opt. Soc. Am. **66**, 709–717 (1976).

[27]E. Zrenner, "Influence of stimulus duration and area on the spectral luminosity function as determined by sensory and VECP measurements," 14th International Society for Clinical Electroretinography, Louisville, Kentucky, 1976. Doc. Ophthal. Proc. Series **12**, 21–30 (1977).

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSMRL Report Number 871	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE ABILITY OF COLOR DEFECTIVES TO JUDGE SIGNAL LIGHTS AT SEA		5. TYPE OF REPORT & PERIOD COVERED Interim report
		6. PERFORMING ORG. REPORT NUMBER NSMRL Report No. 871
7. AUTHOR(s) Jo Ann S. KINNEY, Helen M. PAULSON and A. N. BEARE		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Submarine Medical Research Laboratory Box 900 Naval Submarine Base Groton, Connecticut 06340		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS M0100-PN.001-1005
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Medical Research and Development Command National Naval Medical Center Bethesda, Maryland 20014		12. REPORT DATE 28 March 1979
		13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U. S. Government agencies only; other requests for this document must be referred to the Commanding Officer, Naval Submarine Medical Research Laboratory.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

color-defectives; judging signal lights; color vision;

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measures were made of the ability of color-defective men to judge correctly the colors of navigation lights (red, green, or white) presented to them at night under realistic sea conditions. Eighty-one color-defective men were employed; they were categorized as to type and degree of defect using a battery of five color-vision tests. While the average performance of the color-defective men was considerably poorer than that of 24 color normals, there were large individual differences within each category of defect. Attempts to account for these differences in performance by

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Item 20 -- continued

variations in acuity, intelligence, and motivation failed. The extent to which the data can be accounted for by modern color-vision theory is discussed.